FEASIBILITY STUDY ON
MULTI-CODE SEISMIC EVALUATION
OF A LANDMARK BUILDING

Y. Otsuki\(^1\), K. Buyco\(^2\), M. Kurata\(^3\) and M. Speicher\(^4\)

ABSTRACT
Recognizing the world is becoming increasingly globalized, it can be important for owners of landmark buildings to demonstrate good seismic performance using building codes (or guidelines) from different countries with modern building codes, such as Japan and the U.S. This can improve corporate reputation and competitiveness, and help tenants understand the similarities in risk tolerance between countries. Therefore, this study provides 1) a comparison of design procedures for high-rise buildings in Japan and the U.S. (Los Angeles), 2) a procedure for selection and scaling of ground motions for a landmark high-rise building in Tokyo in accordance with a guideline developed for Los Angeles, and 3) a seismic performance evaluation of the target building. Challenges of assessing the performance of Japanese buildings with U.S.-based methods are discussed. It is demonstrated that designing to an enhanced building performance level in Japan gives similar performance to that recommended in the Los Angeles guideline.

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ABSTRACT

Recognizing the world is becoming increasingly globalized, it can be important for owners of landmark buildings to demonstrate good seismic performance using building codes (or guidelines) from different countries with modern building codes, such as Japan and the U.S. This can improve corporate reputation and competitiveness, and help tenants understand the similarities in risk tolerance between countries. Therefore, this study provides 1) a comparison of design procedures for high-rise buildings in Japan and the U.S. (Los Angeles), 2) a procedure for selection and scaling of ground motions for a landmark high-rise building in Tokyo in accordance with a guideline developed for Los Angeles, and 3) a seismic performance evaluation of the target building. Challenges of assessing the performance of Japanese buildings with U.S.-based methods are discussed. It is demonstrated that designing to an enhanced building performance level in Japan gives similar performance to that recommended in the Los Angeles guideline.

Introduction

Recognizing the world is becoming increasingly globalized, it can be important for owners of landmark buildings to demonstrate good seismic performance using building codes (or guidelines) from different countries with modern building codes, such as Japan, the U.S., Eurocode, etc. as shown in Figure 1. This can improve corporate reputation and competitiveness and help tenants understand the similarities in risk tolerance between countries. For example, following the 2011 Tohoku earthquake, some Japanese building owners who lease their properties to foreign customers have reported difficulty in assuring safety. The problem arose from a lack of evidential information regardless of damages. Information provided to foreign customers and their engineering representatives does not always provide convincing evidence that seismic performance will meet standards accepted in other countries. Part of the challenge is the difference between procedures in the Japanese seismic code and those in the customers’ countries, such as the U.S. Therefore, for building owners to improve corporate reputation and international competitiveness, disclosure of seismic performance through the implementation of different seismic codes is desirable.

State-of-the-art performance-based design methods are now implemented in design practice in seismically-active regions. The U.S. Performance-based design allows structural designers to
select a combination of target hazard levels and design limits. The LATBSDC (Los Angeles Tall Building Structural Design Council) Alternative Procedure [1] is viewed as one of the pioneering guidelines for performance-based design implementation and will thus be used to represent seismic design practice of high-rise buildings in the U.S. This guideline gives a procedure for selecting and scaling ground motions based on the target hazard spectra created by probabilistic seismic hazard analysis (PSHA), which is not reflected in the Japanese code.

For the design of high-rises in Japan, two hazard levels, i.e., Level 1 and Level 2, are considered. The two hazard levels (and associated design spectra) defined in the code have been used in practice for the past decade, the assumed hazard level in the probabilistic seismic hazard map across Japan released by the Japan Seismic Hazard Information Station (J-SHIS), managed by NIED (National Research Institute for Earth Science Resilience), has increased, especially after the 2011 Tohoku earthquake [2]. In response to the observed responses for long-period ground motion against subduction-zone mega-earthquake, there is a movement amongst building owners and practicing structural engineers to consider higher hazard levels than required by code. For example, Nakai et al. [3] reported that, for landmark buildings, engineers often either use hazards 1.5 times higher than the current Level 2 design spectrum or set stricter design limits. In 2016, JSCA (Japan Structural Consultants Association) showed the guideline for performance-based design practice where 1.5 times hazard level is considered for super-class (“Tokkyu” class) buildings [4]. With the new climate of risk in Japan with respect to a powerful inland earthquake and Nankai Trough earthquake, consideration of unexpectedly large earthquakes is likely to continue in the future.

Based on this background, this study aims to present observations based on U.S. performance-based code implementation of an existing Japanese landmark high-rise building. The main objectives of the research are 1) to examine the feasibility of implementing the LATBSDC to an existing Japanese landmark high-rise building and 2) to understand the seismic performance of Japanese high-rise buildings in light of the latest hazard level increases in Japan. For the above objectives to be achieved, this paper presents 1) a comparison of design procedures for high-rise buildings in Japan and the U.S, 2) a discussion of the selection and scaling of ground motions according to the LATBSDC, and 3) a discussion on the resulting seismic performance evaluation.

Figure 1. Concept of accountability of local building owners on building seismic performance to global company tenants.
Overview of Japanese Seismic Code and LATBSDC

The design procedures and criteria for high-rise buildings in the Japanese seismic code and LATBSDC (2015 version) are summarized in Figure 2 and Table 1 [1, 5]. In Japan, a building with a height of more than 60 m is regarded as “high-rise” and requires nonlinear time history analysis and peer review for its structural design. For simplicity and generalization of behavior a “stick model” approach is generally used for dynamic analyses, provided strict limitation and check on torsional responses. Two hazard levels are considered, Level 1 and Level 2, defined by the design spectrum and the associated maximum velocity, which in turn gives approximate return periods. These two hazard levels have not been changed for decades. The purpose of Level 1 evaluation is to insure that a building remains within the elastic range. At Level 2 evaluation, a building is intended to be repairable even if it reaches the plasticity range when subjected to an earthquake whose return period is approximately 500 years. The nonlinear analysis and peer-review examine the maximum story drift and ductility factor for design limits.

The LATBSDC Alternate Procedure for buildings consists of the performance-based requirements, defined by ASCE-7, and the U.S. buildings taller than 49 m regarded as “high-rise” requires assessment by the procedure. The procedure required two level evaluations: serviceability level and collapse prevention level. A building should exhibit serviceable behavior against frequent earthquake ground motions, defined as having 50 % probability of exceedance in 30 years. The building should also exhibit a low probability of collapse against the risk-targeted Maximum Considered Earthquake (MCE), as defined in ASCE 7 [6]. For the hazard definition, either of the uniform hazard spectrum (UHS) and the conditional mean spectrum are used. For collapse prevention level, hazard maps with maximum-direction values must be used while hazard maps with geomean-direction values are permitted for serviceability level evaluations. The building model should be three-dimensional, containing all relevant structural elements. Maximum story drifts are considered for mean and individual values. For collapse prevention evaluation, residual story drifts and strengths of each structural member and story are also examined.

Figure 2. Design procedures of Japanese Seismic Code and LATBSDC.
Table 1. Comparison of design criteria for high-rise buildings in Japan and Los Angeles.

<table>
<thead>
<tr>
<th></th>
<th>Japanese Seismic Code</th>
<th>LATBSDC</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td><strong>Return Period</strong></td>
<td>50 years</td>
<td>500 years</td>
</tr>
<tr>
<td><strong>Target Performance</strong></td>
<td>Elastic</td>
<td>Repairable</td>
</tr>
<tr>
<td><strong>Input Ground Motions</strong></td>
<td>Total of 6 or more design, recorded, and site-specific motions</td>
<td>Total of 6 or more design, recorded, and site-specific motions</td>
</tr>
<tr>
<td><strong>Max. Story Drift</strong></td>
<td>Individual 0.5 %</td>
<td>Individual 1.0 %</td>
</tr>
<tr>
<td><strong>Residual Story Drift</strong></td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Other Requirements</strong></td>
<td>Structural member within elastic range</td>
<td>Story ductility factor less than 2.0</td>
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**Implementation Strategy**

From the above descriptions, we see that the approaches taken for selecting and scaling ground motions and for creating the analysis model are key factors for successful implementation of the LATBSDC assessment on a Japanese landmark building. Selecting ground motions using a UHS is not common in Japan, but was implemented in this study to align with U.S. practice. In Japan, structural design books normally contain the properties and analysis results of the stick model used for dynamic response analysis. Therefore, the simple stick model was used to investigate the LATBSDC guidelines rather than a more complex three-dimensional model which is technically required. Consequently, rather than checking element-level strength requirements using a component-by-component collapse prevention evaluation, we determine the equivalent limits for the stick model. In Japanese code, a ductility factor of 2.0 is specified as the safety limit, which indicates no member deterioration at this level of deformation. For most cases, if the mean story ductility factor against all input ground motions remains at or below 2.0, significant damage to each member is unlikely, and the collapse prevention objective will be achieved. In contrast, if the mean story ductility factor exceeds 2.0, analysis results of a stick model are considered unreliable and a three-dimensional model should be created. Note that this discussion assumes the building of interest went through a strict peer-review in the country where the building is located.
Building Model

The target building shown in Figure 3 (a) is a 238-m-high steel structure with 54 stories above and 6 below ground level. It was designed in 2002 and is located in Tokyo bay area, Japan. The seismic performances in X and Y directions are nearly equal because of symmetric plan. In this study, only the behavior in X direction is considered and its natural period is 5.84 s. A total of 356 semi-active oil dampers and 192 buckling-restrained braces are installed, enhancing the seismic performance of this building compared to those designed to the code minimum level. The spread foundation is designed to be secured to the bedrock layer at a depth of around 30 m.

Based on the structural design information, we created a 61 degree-of-freedom equivalent shear model in OpenSees [8] as shown in Figure 3(b). The nonlinear force-deformation behavior of each story above ground was simulated by a shear spring with a quadrilinear backbone curve. The shear springs of underground stories were set to be linear elastic. The viscous damping was set to 1 % of the critical level at the first natural period and the damping matrix was proportional to the initial stiffness matrix. A Maxwell damper model was used to consider the passive state of semi-active oil dampers. Springs with negative stiffness were inserted to capture large P-Delta effects in the shear model [9]. The natural period of the analysis model was 5.79 s. The validity of the model was verified by comparing the analytical results with responses recorded during the 2011 Tohoku earthquake. Additional details can be found in Otsuki et al. [10].

Selection and Scaling Ground Motions

Preparation for Ground Motion Selection

In LATBSDC, target spectra calculated using PSHA are used for selecting and scaling input ground motions. For this study, the 50 % / 30-year and 2 % / 50-year UHS will be used as the serviceability level and MCE target spectra, respectively. Unlike the U.S. procedure, the Japanese seismic code does not use a UHS and PSHA even though PSHA conducted by J-SHIS across Japan have been available to the public since 2005. Using the information from J-SHIS, in 2007 the Architecture Institute of Japan (AIJ) published UHS at different hazard levels with a 5 % damping ratio for seven major cities in Japan, including Tokyo, as shown in Figure 4(a) [11].

Since the AIJ can be considered one of the most reliable sources of seismic hazard information in
Japan, the AIJ UHS was used as a target spectrum after two modifications. First, the AIJ UHS was created before the 2011 Tohoku earthquake, and thus need to be updated to the latest hazard level. J-SHIS studies indicate that the predicted hazard level in Japan has been increasing since 2011 as described in Figure 4(b). The increase is based on a large effort to recalculate the probabilistic seismic hazard across Japan, including the recalculation of the hazard due to the Nankai Trough [12]. The probability of a Nankai Trough earthquake with a magnitude of 8.0 to 9.0 occurring in the next three decades is 60 % to 70 %, according to some of the latest Japanese government modeling [13]. Second, the AIJ UHS needed to be extrapolated because the spectra were defined only until 5 s, which was not enough for the target building whose first natural period is 5.79 s. Note that the AIJ UHS was created on the basis of the attenuation relation proposed by Kanno et al. [14].

The value of the 5 % damped horizontal acceleration spectra here is the square root of the sum of squares of two orthogonal components in the time domain, which is larger than maximum-direction or geomean-direction value used in LATBSDC. Even though those values are different, this point is not modified to be conservative.

Figure 4. Hazard level in Tokyo: (a) uniform hazard spectra in Tokyo; (b) change of hazard level at the location of the target building.

### Selection and Scaling Procedure for Input Ground Motions

Considering the concerns mentioned above, the AIJ UHS for Tokyo in 2007 was modified and input ground motions were selected and scaled by referring to Moehle et al. [15] and NIST [16] and defining each target spectrum by the corresponding UHS. Figure 5 shows the response spectra of the selected and scaled ground motions compared with the Japanese design spectra. Six out of the seven ground motion records were selected from the 2011 Tohoku and 2003 Tokachi-Oki earthquakes (Japan), and the 2015 Illapel and 2010 Maule earthquakes (Chile) to represent subduction zone hazard in Tokyo. The seventh ground motion record was selected considering all records in the NGA/PEER database [17] and represents the shallow-crustal fault hazard in Tokyo. Selection of each record was made such that the error is minimized between each record’s amplitude-scaled spectrum and the target spectrum. The ground motions were further amplified to account for updates to the seismic hazard in Tokyo from 2005 to 2016 and to meet requirements in ASCE 7-10 that the mean spectrum of the seven ground motions does not fall below the target spectrum for any period from 0.2\(T_1\) to 1.5\(T_1\), where \(T_1\) is the fundamental period of the building. Further details describing this procedure are presented in Otsuki et al. [10]. Note that the procedure for generating input ground motions is not “official,” meaning that it cannot be found in either ASCE 7 or LATBSDC but these codes provide significant flexibility to
the design team with regards to how input ground motions can be selected and scaled for performance evaluation.

Comparison with Japanese Design Spectra

According to Figure 5, at $T_f = 5.8$ s, the mean spectral acceleration for serviceability level was 2.99 times larger than the Level 1 design spectrum. As for MCE ground motions, the mean spectral acceleration at 5.8 s was 1.32 times bigger than Level 2 and 0.88 times smaller than the $1.5 \times$ Level 2 design spectrum.

The large difference between serviceability level ground motions (43-year return period) and Japanese Level 1 design spectra (approximately 50-year return period) is due to a series of conservative approaches and the increase of latest hazard level in Japan. However, it cannot be simply concluded that serviceability level evaluation is more stringent than Level 1 because of the difference in design limits (e.g., Japan-maximum, U.S.-mean story drift limit), and therefore, a dynamic analysis is needed. Comparing MCE with 1.5 times Level 2 ground motions, the hazard level can be regarded as almost the same especially in long periods. Hence, although the definition of $1.5 \times$ Level 2 considered in Japanese design practice is based on engineering judgment, it can be considered a reasonable approach to protect against unexpectedly large earthquakes. However, as ground motion selection approaches are different in two countries, it is still necessary to perform nonlinear dynamic analysis and compare results for the selected ground motions.

![Figure 5](attachment:image)

Figure 5. Acceleration response spectra of selected and scaled ground motions for (a) serviceability level and (b) MCE level, together with the Japanese design spectra.
Seismic Performance Evaluation of Target Building

The seismic performance is evaluated by comparing drift levels to the appropriate limits. Figure 6(a) shows the maximum story drifts of the target building subject to the seven serviceability level ground motions. The results indicate that the target building just meets the design limit of 0.5 % for mean story drift. Even though only a passive state of semi-active oil dampers was considered in this study, the story drift response in an active state will only be decreased by a maximum of 10 % according to the structural design information for the target building. Considering that the target building was designed to have better seismic performance than the minimum requirement in the Japanese seismic code, other Japanese high-rise buildings may have difficulty satisfying the serviceability level requirements with the latest hazard levels published by the J-SHIS.

Figures 6(b)–(d) show the maximum story drifts, residual story drifts, and ductility factors of each story due to the seven ground motions for MCE level. The results show that the target building easily meets the maximum and residual story drift requirements. In addition, the story ductility factors were at most 2.07 and the mean value was 1.50, and thus there is a high possibility the component-level requirements would be met. Therefore, it can be concluded that the target building achieved the collapse prevention objective when subjected to the seven MCE ground motions.

The target building, which has a higher seismic performance than the Japanese minimum code level, satisfied the LATBSDC even considering the latest increased hazard level in Japan. These

Figure 6. Seismic analysis results: (a) maximum story drift against serviceability level ground motions, and (b) maximum story drift, (c) residual story drift, and (d) story ductility factor against MCE ground motions.
results support the conclusion that recent attempts in the Japanese building industry to set a more stringent design limit or use a larger design spectrum function well in addressing unexpectedly large earthquakes in the future.

Summary and Conclusion

The aim of the research stated herein is to examine the feasibility and difficulties in code-mutual implementation and to evaluate how much safety Japanese buildings possess against the latest hazard levels in Japan. The findings through the code comparison and the evaluation of a 54-story Japanese high-rise building by the performance-based design method used in Los Angeles are summarized as follows:

- Due to the lack of up-to-date seismic hazard spectra in Japan, a procedure for creating the latest version of UHS for Tokyo is proposed by combining the UHS published by AIJ in 2007 and the seismic hazard map published by J-SHIS.

- While the assumed return period for Japanese Level 1 and that for serviceability level in LATBSDC are almost same, the spectral acceleration for serviceability level for Tokyo was approximately 2 or 3 times larger than that of Level 1 at longer periods. This is because the ground motion levels assumed in the Japanese design code have not changed since 1981 but the hazard level calculated by PSHA considering the latest research has become much higher.

- The spectral acceleration of MCE ground motions for Tokyo is at the same level of that of 1.5 times the Level 2 design spectrum recently used in design practice in Japan. Although the recent approach by the Japanese building industry to design landmark high-rise buildings surpassing the minimum requirements (1.5 × Level 2) is based on engineering judgment, it is effective as a defense against unexpectedly large earthquakes in the future.

- The results from the LATBSDC implementation depend on which version or year of Japanese hazard level should be adopted. If the target building had been evaluated on the basis of the hazard level at the time of design in 2002, it might have satisfied the design limits with a reasonable margin. In contrast, adopting the latest hazard level may lead to LATBSDC indicating unacceptable performance in a high-rise building designed to the Japanese code minimum level.

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Disclaimer

The study herein presents results comparing design approaches in Japan and the U.S., including an estimate of the performance of an existing high-rise building. This study does not constitute an official endorsement or warranty on the part of NIST or the authors. Users of information
from this study assume all liability arising from such use.

References


